Effect of human and sheep lung orientation on primary blast injury induced by single blast

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Abstract. The intensity and type of trauma inflicted on a bod y by blast overpr essure are related to man y facto rs. Among them, body orientation. In order to study the effect of body orientation, detailed models of 2D horizontal slices of human and sh eep thoraces have been de veloped and va lidated with the limited data available in the op en literature. The main goal o f this stud y is to verify if the injuries observed in the animal are trul y representative of human lung injuries for simple blast lo adings at different orientations to the blast. In tota l, twelve blast directions were sim ulated for three diff erent blast injur y l evels based on the Bowe n curv es. The s heep and the hum an tors os were rota ted according to the ir vertic al axis i n increments of 30 degree star ting from 0 degree through to 330 degree. From this study, it is predicted that the greatest reduction in lung primary blast injuries may be come from focusing on protecting the torso from -60 deg to +60 deg. Results showed also, that sheep are more d ependent to the blast wave duration and orientation.

1. INTRODUCTION

Explosions ha ve t he potential t o ca use l ife-threatening i njuries (e .g. blunt, pe netrating wounds a nd bl ast overpressure in juries). Mo st b last inj uries traditionally are d ivided i nto three m ajor categ ories: p rimary, secondary, and tertiary in juries. A person may be in jured by m ore than one of these mechanisms in any given event. Primary blast in juries (PBI) a re exclusively caused by the blast overpressure. A PBI usually affects air-containing organs such as t he lung, ears and gastrointestinal tract. Secon dary b last inj uries are caused by fragments that impact the body. Tertiary blast injuries include traumatic amputation and injuries sustained due to whole body displ acement includi ng im pact (e.g. being thrown a gainst anot her object) [Ref. 1].

There is a need to understand and predict this type of injury in order to improve, develop and optimise protection. In th is o ptic, a numerical fin ite ele ment (FE) m odel was b uilt to pred ict b last in jury fro m simple blast overpre ssures [Ref. 2]. Using an ad vanced non -linear FE m ethod, arbitr ary Lagr angian-Eulerian f ormulation (ALE), t wo-dimensional m odels of t he human an d s heep t orsos we re c onstructed. The main goal of this study was to find a co rrelation between the prediction of lu ng injury in sheep and human, particularly as a funct ion of orientation with respect to the blast wave, and to verify if the injuries observed in the sheep are truly representative of human lung injuries for a given blast loading condition.

2. BLAST WAVE IN AIR

Major conventional high explosives release, in a relatively short amount of time, a large quantity of energy through exp ansion of th e gaseous detonation pr oducts. This r esults in an overpressure w ave t hat also commonly call ed blast wav e. Th e passage of the blast wave through a particular position away from the detonation can be charact erized as sim ple or com plex depending on the time hi story of the overpressure observed at that p osition. A si mple b last-wave pressure disturbance resu lting fro m an id eal ex plosion in free field has the shape of a Friedlander curve. In th e Fr iedlander curve, the pressure is comprised of a positive phase characterized by an instantaneous rise to the peak overpressure followed by a rapid decay of the overpressure. Thi s is followed by a longer but low magnitude negative pressure phase before a return to ambient co nditions as sho wn in Figu re 1. C omplex blast wav es can b e described as an y loading th at does not fall un der the description of a simp le blast wave and is typ ically characterized by multiple peaks and a c omplex waveform. T his type of waveform is characteristic of all bu t the most idealized real world loading an d is th e resu lt o f multiple wav e reflectio ns off o bjects in the en vironment su ch as th e ground,

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14. ABSTRACT

The intensity and type of trauma inflicted on a body by blast overpressure are related to many factors. Among them, body orientation. In order to study the effect of body orientation, detailed models of 2D horizontal slices of human and sheep thoraces have been developed and validated with the limited data available in the open literature. The main goal of this study is to verify if the injuries observed in the animal are truly representative of human lung injuries for simple blast loadings at different orientations to the blast. In total, twelve blast directions were simulated for three different blast injury levels based on the Bowen curves. The sheep and the human torsos were rotated according to their vertical axis in increments of 30 degree starting from 0 degree through to 330 degree. From this study, it is predicted that the greatest reduction in lung primary blast injuries may be come from focusing on protecting the torso from -60 deg to +60 deg. Results showed also, that sheep are more dependent to the blast wave duration and orientation.

15. SUBJECT TERMS

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buildings, the walls of an enclosure, etc. Figure 1 shows also a comparison between a real blast wave for a free field test with an elevated cylindrical charge and the idealized Friedlander approximation.
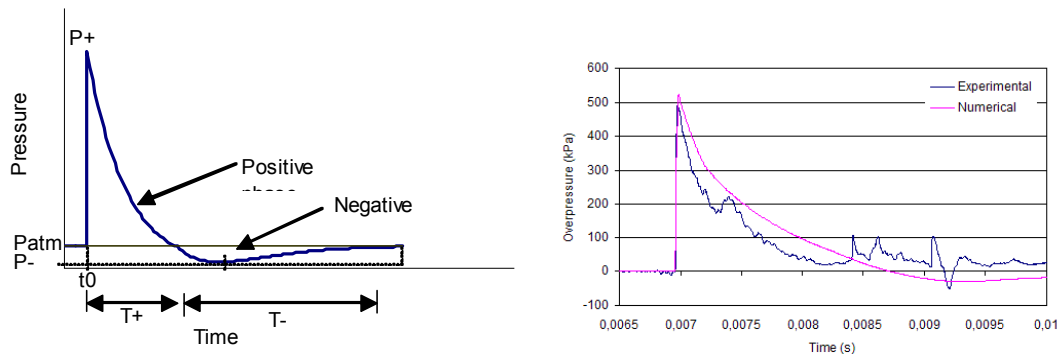

Figure 1. Typical Friedlander pressure curve (left), comparison between a real blast wave and a Friedlander approximation, case: 5 kg C4 at 2.5m (right).

For simplicity of the modeling approach at this stage of the blast injury study, the blast loading considered has been assumed to follow a Friedlander pressure curve as a reasonable idealization of free field blast loading.

3. BOWEN CURVES

The Bowen curves [Ref. 3] were generated from a wealth of data, primarily from shock tube testing of two groups of animals: small animals (e.g. mice, pigs and rabbits) and large animals (e.g. monkeys, sheep and swine). Scaling rules were applied to generate injury thresholds and predictions of lethality for a human. The Bowen curves are often used as a simple model to estimate primary injuries from a simple (Friedlander) blast loading. Figure 2 shows the Bowen curves for a man oriented perpendicular to the blast direction. In this figure, two versions of curves are given: The original curves [Ref. 3] and a new set of survivability curves by Bass *et al.* [Ref. 4] based on a complete reanalysis of the original data supplemented by additional data from more recent sources. This study was performed using the revised curves by Bass *et al.*
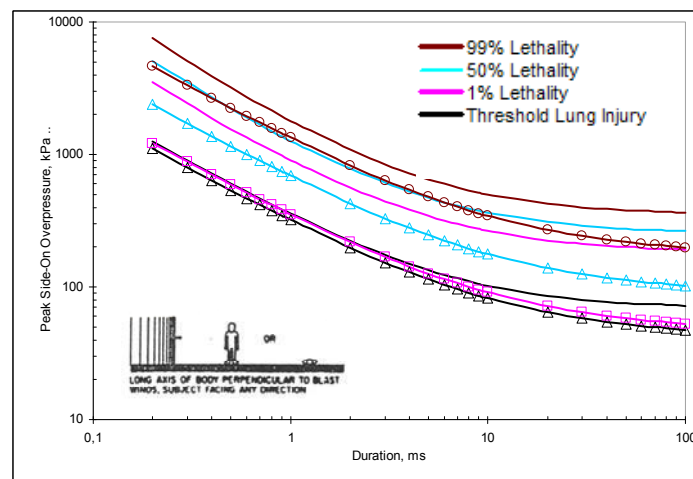

Figure 2. Original (dashed lines [Ref. 3]) and new Bowen curves (dashed lines with symbols [Ref. 4]) for a man oriented perpendicular to the blast direction

Three Fri edlander (simple blast) c urves that represent th e th reshold lev el (TH), 1% an d 50% probability o f lethality (LD$_1$ and LD$_{50}$) f or du rations e qual t o 2 ms on the re vised B owen c urves w ere selected. These curve s a nd their c haracteristic peak pressures a nd dura tions a re listed in Ta ble 1. An abbreviation for these curves is used throughout the article. For example, TH-T$_2$-P$_{200}$ refers to a thre shold blast wave with duration equal to 2 ms and a peak overpressure of 200 kPa. LD$_1$-T$_2$-P$_{500}$ refers to an LD$_1$ blast wave with duration equal to 2 ms and a peak overpressure of 500 kPa.

Table 1. Characteristics of the blast waves using during the simulations

TH		LD$_1$	LD$_{50}$
Peak overpressure, kPa	200	500	700
Positive phase duration, ms	2	2	2

From the wo rk do ne by O' Brien *et al.* an d Coop er *et al.* [Refs. 5, 6], pressure w ithin the lung, exposure time and the rise time of the pressure are proposed as indicat ors of l ung trauma. Experi mental tests involving measurements of the intra-thoracic peak pressure suggested a threshold between 70 kPa and 110 kPa fo r human lu ngs [Ref. 7]. Lack ing an y direction from th e o pen literatu re on si milar sh eep-lung injury thresholds, the 70 kPa threshold was also used to quantify the sheep lung injuries in this study.

4. FINITE ELEMENT MODEL OF THE HUMAN AND SHEEP MODELS

The hu man an d sh eep m odels d escribed in th is sectio n were in itially g enerated b y Th e Un iversity o f Waterloo under a cont ract from DRDC Val cartier [R ef. 2] and base d on the work done by O'Brien *et al.* and Coop er *et al.* [R efs. 5, 6]. Fi gure 3 s hows a t op vi ew of t he numerical an d CT-scanned h uman an d sheep t orso c omponents. T he hum an m odel was creat ed fr om im ages fr om the Vi sible Hum an Pro ject, National Library of M edicine [Ref. 8]. As s uch, the model is representative of an 8 2 kilogram, 1.8 m eter high man with the slice taken at the fifth and sixth thoracic vertebrae. The sh eep model was created using pictures from an atlas of x-ray anatomy of sheep [Ref. 9] and is therefore representative of the two-year old 56.6-kilogram ewe used t o generate the atl as. The m odel represents a slice at the fifth and sixth thoracic vertebrae level.
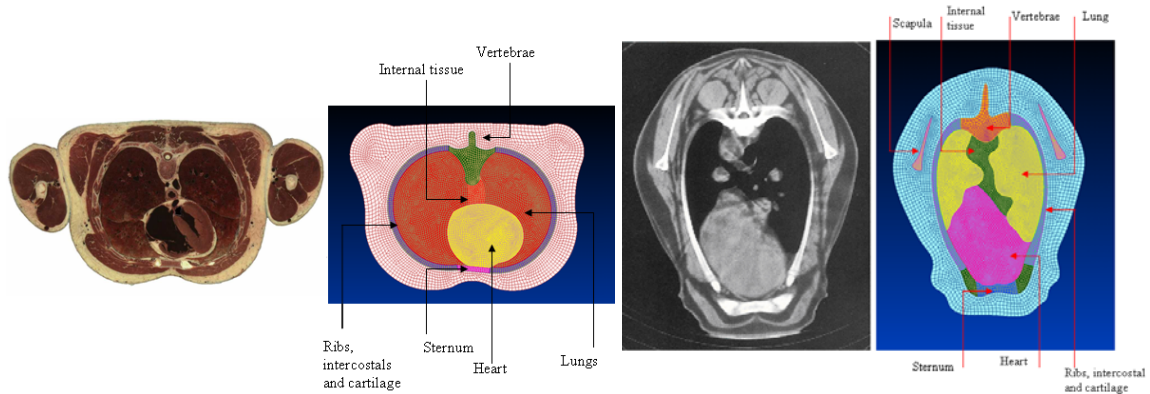

Figure 3. A top view of the numerical and actual human (left) and sheep (right) torso components [Ref. 2]

The LS-Dyna hy drocode was use d t o simulate t he co upled human/sheep t orso a nd blast w ave [Ref. 10]. Several methods for creating blast overpressure loading on solids in LS-Dyna were investigated. Among them, is modeling the detonation of an ideal explosive using *LOAD_BLAST card implemented in LS-Dyna. In this method, a pressure-time history is applied on each element of the torso. This method was not used si nce coupling bet ween t he blast flow a nd the torso is signi ficant in accura tely predicting the

energy trans fer to the tissue. Th e ot her m ethod i s an Ar bitrary-Lagrangian-Eulerian (ALE) f ormulation [Ref. 10]. This method wa s chosen for its flexibility as it allows th e desire d overpress ure and pulse duration t o be ge nerated wi th a m ore real istic repre sentation of c oupling bet ween t he bl ast wa ve and resulting fl ow and the thorax. In order to maintain the ALE coup ling, the sizes of the sh eep and human elements were kept equal or smaller than the size of the air elements surrounding the torso. The size of the sheep and human elements varies from 2.5 mm to 5 mm. The human and the sheep models were modeled in a way that they can move with the blast. They boundaries were not fixed in x and y directions.

The human and s heep model featured four layers of elements through the thickness of th e quasi 2D slice. Because of the three-dimensional nature of the rib cage, the model was divided into two components (2 elements though the thickness per components): a bone-level where the rib cage is represented by bone and an intercostal-level where the structure of the rib cage is cap tured by modeling the in tercostal muscle tissue. The different cha racteristics of b one (e .g. t he ribs) a nd m uscle ha ve a n i nfluence o n wave propagation and h ence on t he in jury th at develops behind th e rib cag e. Fin ally, an ex tensive literatu re review focused on human and animal tissue material properties was performed by University of Waterloo to determine the relevant inputs for the constitutive models used to represent each material [Ref. 2].

4. EFFECT OF BODY ORIENTATION ON THE BLAST INJURY

The i ntensity and t ype of t rauma i nflicted on a body by bl ast ove rpressure a re rel ated t o m any fact ors. Among theme, body orientation. In o rder to study this factor, the sheep and h uman models were exposed to blast wave s from differe nt sides. In tot al, twelve ori entations were simulated at three different bl ast injury levels that correspond to the 2 ms overpressure duration (TH-T_2-P_{200}, LD$_1$-T_2-P_{500} and LD$_{50}$-T_2-P_{700}). The s heep a nd the hum an torsos were rotat ed thei r ve rtical axes in 30 degree increments starting from 0 through to 330 degrees in the clockwise direction. The position corresponding to 0 deg orientation is shown in Figure 4 and tt's corresponding to a man facing the blast wave. The position of the sheep is the one that was used in the experimental tests done by Bowen [Ref. 3].
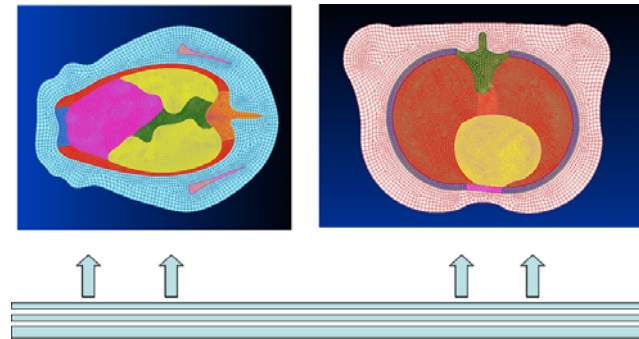

Figure 4. Blast wave direction, 0 deg orientation

The average of the maximum overpressure of twelve elements located in the human torso lung model and six elements located in the sheep-lung m odel, as shown in Figures 5 and 6 respectively were generated from the FEM. These pressures were averaged from virtual gauges in both the intercostal and rib layers of the mesh.

Polar plots of the av erage max imum o verpressure g ive a q ualitative assessm ent o f th e effect o f th e blast orientation on the human and sheep torso injuries. In the human model, the average of the G1 to G4 virtual gauge maximum overpressures is referred to as the *back* curve. The curve labelled *mid* corresponds to the ave rage of t he G5 to G8 virtual ga uge m aximum overpressures and the cu rve l abelled *front* is th e average of the G9 to G12 virtual gauge maximum over pressures. In the sheep thorax, the cu rve l abelled *left* represents the average of virtual gauges G1 and G2 maximum overpressures. The c urve labelled *right* is the average of G3 and G4 gauges maximum overpressure data and the curve labelled *up* corresponds to the average of the G5 and G6 virtual gauge maximum overpressures.
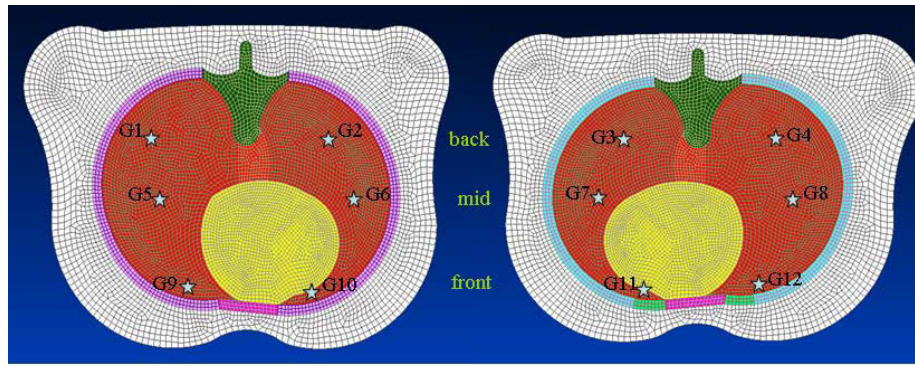
Lower side, intercostal   Upper side, bone

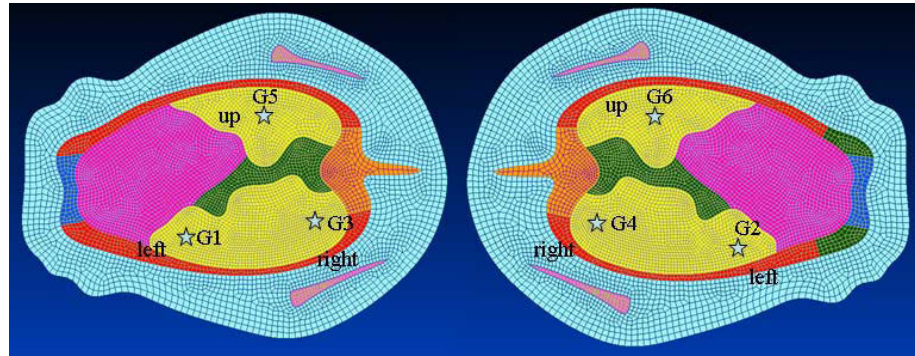**Figure 5**: Gauge locations for body orientation inputs, human

Figure 6: Gauge locations for body orientation inputs, sheep

4. RESULTS AND DISCUSSION

Figure 7 shows a polar plot of the maximum human and sheep lung pressures as a function of orientation of the blast loading. From the TH-T_2-P_{200} figures, when the blast impacts a human torso at angles varying between 330 deg to 30 deg in the clockwise direction, the blast is predicted to induce significant lung injuries. In the sheep, the TH-T_2-P_{200} blast is predicted to be below the threshold for injury irrespective of the orientation.

The same trend observed from the LD_1-T_2-P_{500} loading (Figure 9) is also noted when using the LD_{50}-T_2-P_{700} loading history. The LD_{50}-T_2-P_{700} blast is predicted to have slight effects on the human lungs in the case where the torso is in the 120 deg to 240 deg positions (clockwise direction). If this reduced sensitivity to blast in these orientations can be proven in humans, it could be a significant driver when designing future protection systems. For example, the blast protection for the torso could cove the arc from 300 to 60 deg in the clockwise direction. In the sheep case, only the 180 deg case induces slight blast injuries in the lungs with significant injuries being predicted in at least one lung in all other cases.
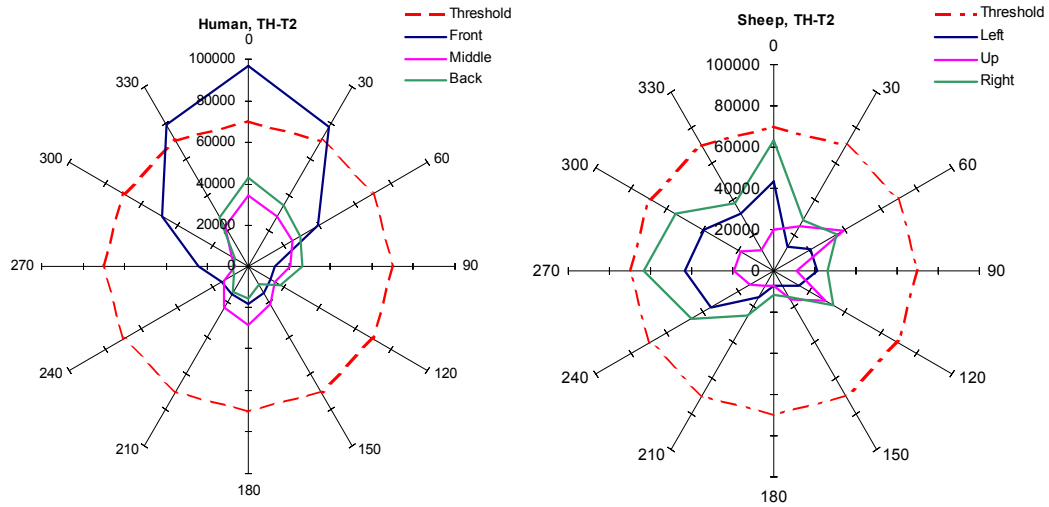
Figure 7: Maximum human (left) and sheep (right) lung overpressure for different orientations with respect to the blast origin, TH-T_2-P_{200}
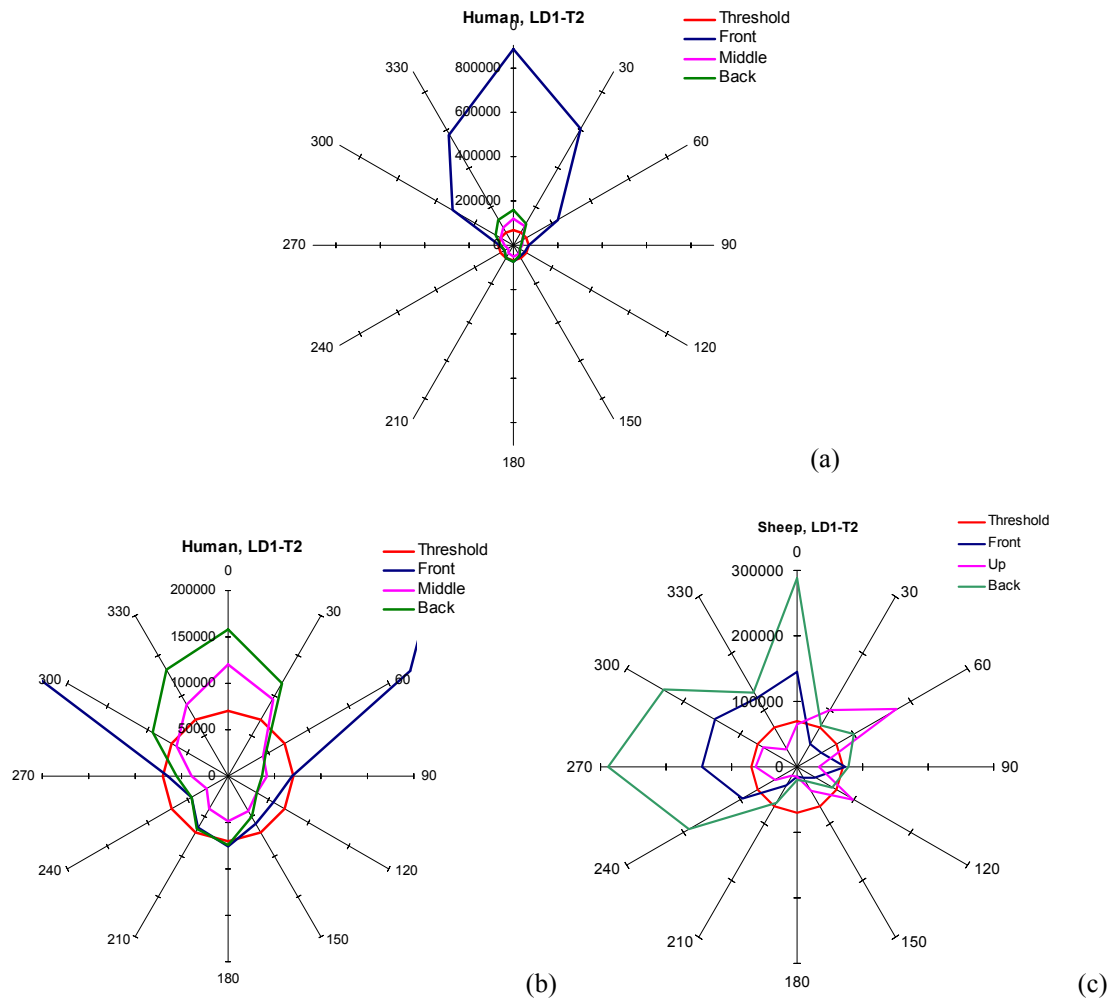

(a)

(b)

(c)

Figure 8: Maximum human (a, b) and sheep (c) lung overpressure (in Pa) for different orientations with respect to the blast origin, LD$_1$-T_2-P_{500}
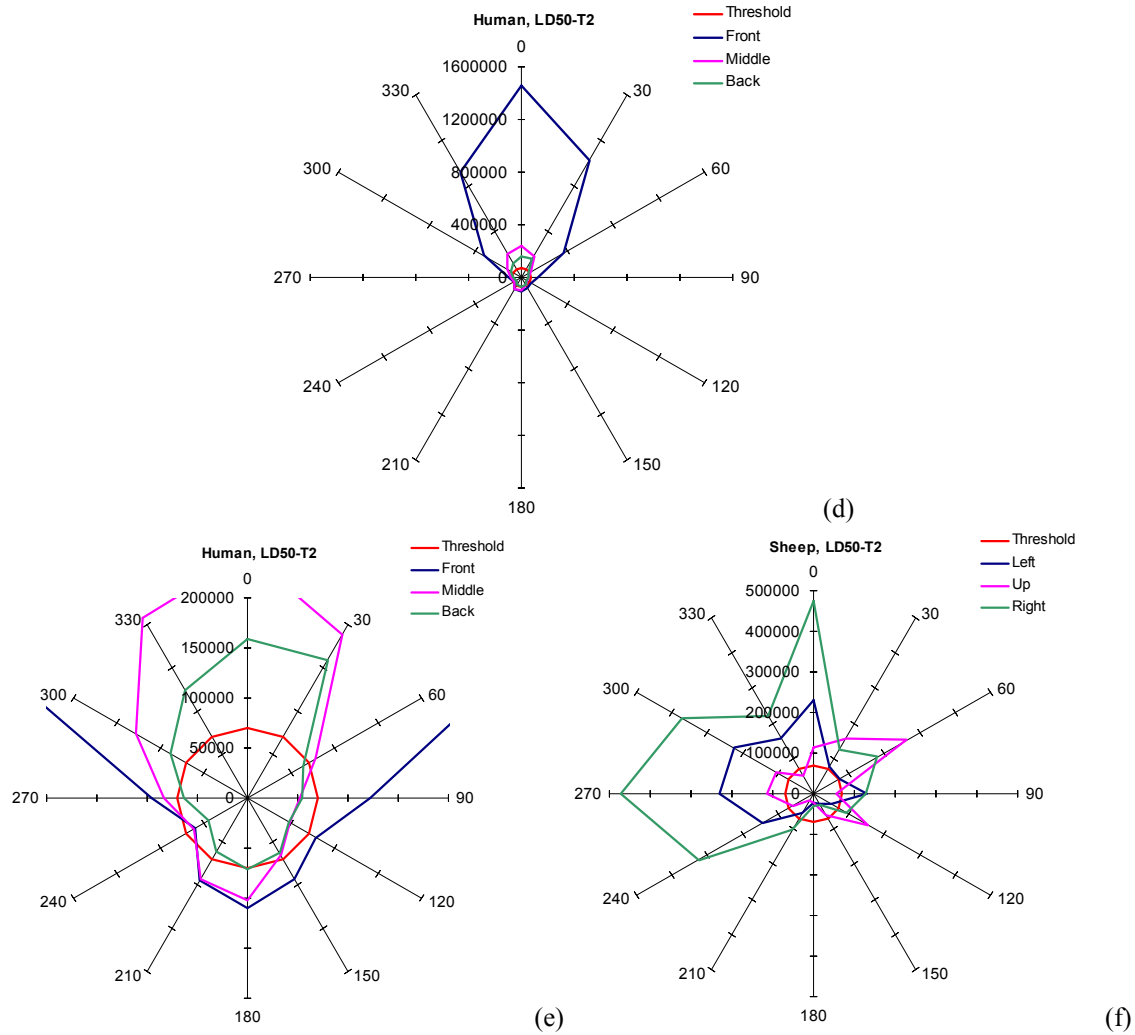
Figure 9: Maximum human (d, e) and sheep (f) lung overpressure (in Pa) for different orientations with respect to the blast origin, LD_{50}-T_2-P_{700}

CONCLUSION

Quasi two-dimensional FE models of a human and sheep thorax were developed using the non-linear arbitrary Lagrangian-Eulerian formulation in LS-Dyna. The FE models were applied to studies of the effect of body orientation to the blast wave. The parametric study showed that there is an effect of body orientation on blast injuries predicted in human and sheep models. From this study, it is predicted that the greatest reduction in lung PBI may be come from focusing on protecting the torso from -60 deg to +60 deg measured in the horizontal plane relative to the long axis of the body. Further enhancements can be made to the torso model. First, other two-dimensional slices taken at different levels in the human and sheep thoraces, or indeed a full three-dimensional human and sheep torso model, should be modelled since only injuries between the fifth and sixth vertebrae level were studied and generalized as predictors of overall lung injury. Second, the model developed in the present study does not allow wave propagation in the vertical direction (principle axis of the body). Also, material properties and constitutive model specially for lung tissues need to be investigated in order to increase the accuracy of the numerical results. Finally, the next step of this study is to investigate different thoracic blast protection concepts.

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